The Evolution of Procyon A

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Abstract. A grid of stellar evolution models for Procyon A has been calculated. These models include the best physics available to us (including the latest opacities and equation of state) and are based on the revised astrometric mass of Girard *et al.* (1996). The long standing discrepancy between the evolutionary mass and the astrometric mass is now resolved, a result of the newly determined astrometric mass. Models were calculated with helium diffusion and with the combined effects of helium and heavy element diffusion. Oscillation frequencies for $\ell = 0, 1, 2$ and 3 p-modes (and g-modes) were calculated for these models. The predicted p-mode frequencies are relatively unaffected by heavy element diffusion and convective core overshoot. The inclusion of a modest stellar wind which effectively suppresses the helium diffusion in the surface layers has a modest effect on the p-mode frequencies. The evolutionary state (main sequence or shell hydrogen burning) of Procyon A has the largest effect on the predicted p-mode frequencies. The g-modes show a greater sensitivity to the various model parameters.

The Procyon binary system consists of an F5 IV-V primary and a white-dwarf secondary in an 40.8 year orbit. The F5 primary (Procyon A) is a bright, nearby star with a well determined parallax and astrometric mass. As such, it presents a unique target for the study of non-radial stellar oscillations. Previous theoretical studies have pointed out that the astrometric mass was incompatible with the mass derived from stellar evolution calculations (Guenther & Demarque 1993). Procyon A was the target of a multi-site observing campaign (10 – 31 Jan/97) by the SONG project, whose goal was the detection of stellar oscillations. Motivated by these observations, as well as an improved mass determination for this star, we have re-examined the evolution and pulsation properties of Procyon A. The fundamental properties of Procyon A are:

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$M = 1.50 \pm 0.05\,\mathrm{M}_\odot$ (Girard *et al.* 1996), $\pi = 0.2832'' \pm 0.0015$ (Girard *et al.* 1996), $F = (18.64 \pm 0.87) \times 10^{-6}\,\mathrm{ergs\,cm^{-2}}\,s^{-1}$ (Smalley & Dworetsky 1995) and an angular diameter of $\phi = 5.51 \pm 0.05\,\mathrm{mas}$ (Mozurkewich *et al.* 1991) which imply $L = (7.22 \pm 0.35)\,\mathrm{L}_\odot$ and $R = (2.09 \pm 0.02)\,\mathrm{R}_\odot$.

Models for Procyon A were calculated using the Yale stellar evolution code, in its non-rotating configuration (Guenther *et al.* 1992). These models included the latest OPAL opacities (Iglesias & Rogers 1996) and the OPAL equation of state (Rogers *et al.* 1996). The diffusion coefficients are from Thoul *et al.* 1994. Most of the models only included helium diffusion. A single model which included both helium and heavy element diffusion (treated as a single mean heavy element, Z) was evolved to study the effects of heavy element diffusion on Procyon A. The models included the effects of a wind mass loss in the diffusion equations. A wind velocity of $v_w = -\dot{\mathrm{M}}/(4\pi\rho r^2)$ was included in the diffusion equations, and a solar mass loss rate $\dot{\mathrm{M}} = 2 \times 10^{-14}\,\mathrm{M}_\odot/\mathrm{yr}$ was assumed. This wind velocity was large enough to effectively suppress the diffusion in the outer layers of the model. One model was calculated without wind loss.

The models for Procyon A were evolved from the ZAMS until they reached the observed radius. In an iterative procedure, the helium abundance was adjusted in the ZAMS model and the model was re-evolved, until the model matched the observed radius and luminosity of Procyon A. The starting helium abundance was constrained such that $1.5 < \Delta Y/\Delta Z < 4$. In addition, the final surface abundance of Z/X was constrained to be within 0.1 dex of the solar value $Z/X = 0.0245$ (Grevesse & Noels 1993), to satisfy the observed constraint that the surface abundances of Procyon A are near solar. Models which met all of the above criteria had their pulsation frequencies calculated using Guenther's nonradial nonadiabatic stellar pulsation program (Guenther 1994).

In total, 8 different calibrated models of Procyon A were calculated and pulsed (Table 1). The standard model (line 1 in Table 1) uses the best estimate for the mass ($1.5\,\mathrm{M}_\odot$), does not include heavy element diffusion or overshoot at the convective boundaries, and uses our calibrated solar value for the mass fraction of the heavy elements (Z). The other 7 models involved changing a single parameter from the standard model: (a) low heavy element abundance (low Z); (b) heavy element diffusion (Z diff); (c) convective core overshoot of 0.1 pressure scale heights (overshoot); (d) evolution to a somewhat lower luminosity (low L); (e) higher mass (high M) (f) lower mass (subgiant); and (g) no wind loss. All but the subgiant model are in the main sequence phase of evolution. The lower mass model is in the hydrogen shell burning phase of evolution. Table 1 includes the characteristic frequency spacing Δ of the p-modes, which is approximately equal to the average frequency separation between adjacent in n p-modes, likely to be the first quantity determined by stellar seismology. Table 1 also includes the characteristic period spacing Π of the g-modes. The frequencies and characteristic frequency spacings depend on the radius of the star. To first order, $\delta\mathrm{R}_*/\mathrm{R}_* \simeq \delta\nu/\nu$. The radius of Procyon A is known to within 1% . Thus, the calculated pulsation frequencies are uncertain at the 1% level due to the error in the radius. In addition, uncertainties in the modeling of the superadiabatic layer (in both the evolution and pulsation calculations) leads to an estimated uncertainty of $\sim \pm 0.5\%$ in the p-mode frequency calculations (see Guenther & Demarque 1996). The total error associated with the calculated pulsation fre-

quencies shown in Table 1 is approximately $\sim 1.5\%$. Thus, differences in Δ greater than $\sim 1\mu$Hz are significant. From Table 1 we see that only the subgiant model has a Δ which is significantly different from the others. This suggests that the detection of the average frequency separation between adjacent in n p-modes will be able to determine the evolutionary status of Procyon A (or, indicate that the models are in error).

Table 1. Model Characteristics

Model	Mass ($M_\odot$)	Z	$\Delta Y/\Delta Z$	$Z/X_{\rm env}$	$M_{\rm core}$ ($M_\odot$)	$M_{\rm scz}$ ($M_\odot$)	log ($L/L_\odot$)	Δ (μHz)	Π (μHz)
Standard	1.50	0.018	3.03	0.0253	0.118	1.17E–4	0.85868	54.70	60.58
low Z	1.50	0.015	2.02	0.0206	0.107	1.15E–4	0.85860	54.70	56.35
Z diff	1.50	0.018	3.01	0.0253	0.118	1.19E–4	0.85847	54.70	60.70
overshoot	1.50	0.018	2.53	0.0248	0.133	1.04E–4	0.85848	54.73	64.77
low L	1.50	0.018	2.47	0.0243	0.113	2.31E–4	0.83747	55.02	59.35
high M	1.54	0.018	1.90	0.0247	0.121	1.07E–4	0.85854	55.47	61.65
subgiant	1.40	0.018	2.94	0.0239	0.000	5.62E–5	0.85838	52.91	16.87
no wind	1.50	0.018	3.12	0.0196	0.122	1.36E–5	0.85852	53.66	62.02

The characteristic period spacing (Π) of the g-modes shows a much larger variation than Δ (Table 1). Once again, due to errors in the models and radii of Procyon A, only differences in Π greater than $\sim 1\mu$Hz are significant. In this context, it is clear that the detection of g-modes in Procyon A would allow one to (a) determine its evolutionary status; and (b) determine if appreciable overshoot ($\gtrsim 0.05\,H_p$) is occurring at the edge of the convective core in Procyon A, and/or provide an estimate of the interior metallicity of Procyon A.

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